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Effect of Frequency-Dependent Soil Parameters on Reflection Coefficients

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The degree with which electromagnetic pulse (EMP) energy is predicted above a reflecting plane is strongly dependent on the nature of the plane. The reflection of electromagnetic energy from a surface can be accurately described mathematically, and equations which predict these fields are common knowledge to the EMP community.

Although this is the case, some predictive analysis uses models for the earth's surface which are independent of frequency and considers only an average soil moisture content.

20. ABSTRACT (Cont'd)

This report describes the varieties of electrical properties with frequency and moisture content. It applies these variations to a reflected EMP and assesses the energy difference between models which use parameters independent of frequency and those which use varying parameters. Finally, it discusses the variation of soil properties with depth and predicts the magnitude of energy, above the ground, which may result from this variation.

CONTENTS

FIGURES

FIGURES (Cont'd)

TABLES

1. INTRODUCTION

If the conductivity and dielectric constant of two distinct media are known, the amount of electromagnetic energy which will be reflected at their interface can be related to the incident energy through the Fresnel equations. On a large scale, the earth-air boundary is an example of such an interface. In comparison to the earth, the electrical properties of the air can be considered relatively independent of regional variations. Therefore, obtaining typical electrical properties of the soil in a particular region becomes a primary objective if the reflection coefficients are desired.

With regional values, the reflection of electromagnetic energy, such as that encountered after a high-altitude nuclear burst, can be calculated. Without regional values, however, the spectrum of energy reflected may be inadequately predicted. Any method of approximating conductivity and dielectric constant will produce an error if it excludes regional variables such as structure or mineral content, or if it excludes frequency and moisture content. To determine whether this error should cause significant concern, the actual values for conductivity and dielectric constant can be measured and compared with predicted values. In this way, the reflected energy spectrum can be more accurately predicted.

2. SOIL PARAMETERS

In order to determine the energy of a pulse wave reflected from the surface of the earth, the electrical properties of this soil/air boundary must be known. The Fresnel equations, which describe the reflection of electromagnetic energy, require that the conductivity, permittivity, and permeability of both the air and the soil be known. Under normal conditions, and in comparison to soil, the electrical properties of air are approximately equal to those of free space. Therefore, determining the electrical properties of the earth becomes a primary concern.

Several studies have been conducted concerning the electrical properties of the soil. The results of these studies state that the conductivity (σ) and permittivity (ϵ) can be predicted at a specified frequency, if the moisture content is known. The permeability (μ), which is a function of the ferrous mineral content, deviates slightly from that of free space in most regions.

Scott[1] measured numerous samples over the frequency range of 10^2 to 10^6 Hz. After averaging his data, he produced a set of curves for

[1]*J. H. Scott, Electrical and Magnetic Properties of Rock and Soil, U.S. Geological Survey, Note 18 (1966).*

conductivity and dielectric constant as functions of frequency. These curves, which have become known as Scott's universal curves, have been curve fit with a second-order surface fit and are mathematically represented in equations (1) and (2).

Scott's curve fit for conductivity is

$$K = -0.604 + 1.640W - 0.062F + 0.062W^2 - 0.070FW + 0.021F^2; \quad (1)$$

the curve fit for relative dielectric constant is

$$D = 4.905 + 1.308W - 0.971F + 0.111W^2 - 0.160FW + 0.059F^2, \quad (2)$$

where

$K = \log_{10}$ of conductivity (mmho/m),
$D = \log_{10}$ of dielectric constant $(\varepsilon/\varepsilon_0)$,
$W = \log_{10}$ of water content (percent by volume), and
$F = \log_{10}$ of frequency (Hz).

Since Scott's work encompasses a large variety of laboratory-measured soil samples (samples which correlated well with field measurements), equations (1) and (2) give an average of conductivity and dielectric constant over various regions.

C. L. Longmire[2] developed a time-domain representation called the universal RC network model (fig. 1). The basic assumption of this model is that the soil can be regarded electrically as an equivalent network of resistors and capacitors. Longmire made no laboratory measurements, but by using Scott's curves and data that he received by private consultation with Wilkenfeld,[2] he extended the expected validity of his model over the frequency range of 10^0 to 3×10^{12} Hz.

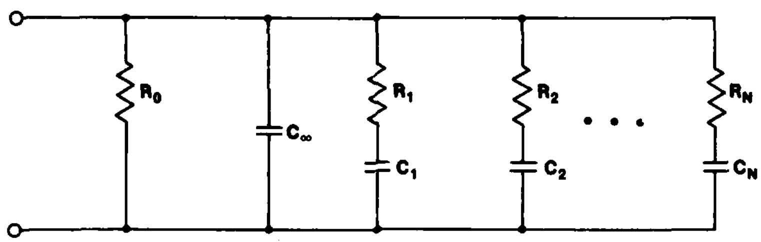

Figure 1. Universal network model.

[2]*C. L. Longmire, A Universal Impedance for Soils, Defense Nuclear Agency, DNA 3788T (1975).*

Longmire's model states that

$$C_\infty = \varepsilon_0 \varepsilon_\infty \quad , \quad C_n = \varepsilon_0 a_n \quad ,$$

$$R_o = \sigma_0^{-1} \quad , \quad R_n = \frac{1}{2\pi f_n C_n} \quad ,$$

where

C is capacitance,
a is a constant,
R is resistance,
R_o is the resistance of the circuit that is asymptotically approached as frequency is decreased,
σ is conductivity,
f is frequency, and
the subscript ∞ indicates a value which is asymptotically approached as frequency is increased.

The relative dielectric constant of the soil is

$$\varepsilon_r = \varepsilon/\varepsilon_0 = \varepsilon_\infty + \sum_{n=1}^{N} \frac{a_n}{1 + (f/f_n)^2} \quad , \tag{3}$$

and the conductivity is

$$\sigma = \sigma_0 + 2\pi\varepsilon_0 \sum_{n=1}^{N} a_n f_n \frac{(f/f_n)^2}{1 + (f/f_n)^2} \text{ (mho/m)} \quad , \tag{4}$$

where f_n accounts for moisture content. Table 1 gives coefficients for universal soil as derived by Longmire's model.

TABLE 1. COEFFICIENT a_n FOR UNIVERSAL SOIL

n	a_n	n	a_n	n	a_n
1	3.40×10^6	6	1.33×10^2	11	9.80×10^{-1}
2	2.74×10^5	7	2.72×10	12	3.92×10^{-1}
3	2.58×10^4	8	1.25×10	13	1.73×10^{-1}
4	3.38×10^3	9	4.80		
5	5.26×10^2	10	2.17		

To obtain a standard for evaluating the error which might be incurred by applying the results of this network model in a region which does not follow the typical soil parameters, laboratory measurements were made of ϵ_r and σ for five samples of soil taken from the Harry Diamond Laboratories, Woodbridge Research Facility, Woodbridge, VA. The National Bureau of Standards conducted these measurements over the frequency range of 5×10^6 to 6×10^8 Hz. Following Scott's work, a second-order surface fit was made for these data as given in equations (5) and (6):

$$D = 5.886 - 1.045F - 2.055W + 0.077FW + 0.056F^2 + 1.180W^2 \quad , \qquad (5)$$

$$K = -3.233 + 0.6453F - 0.448W - 0.105FW - 0.0113F^2 + 0.8876W^2 \ . \qquad (6)$$

Equations (5) and (6) are henceforth referred to as the varying regional parameter equations.

The averaged values at 5-, 10-, 15-, 20-, and 25-percent moisture content for conductivity and dielectric constant are shown in figures 2 and 3. Also shown are the values predicted by the Longmire universal network model for 10-percent moisture content (eq (3) and (4)).

As can be seen from figure 3, averaged values for conductivity are considerably below the values predicted by the network model. Since these data were obtained in a region of higher than average rainfall, and taken from the uppermost soil, it is believed that their values indicate only that the surface soil possesses a low conductivity. Several other field measurements were taken near the laboratory, measurements which indicate that the conductivity of the soil increases sharply a few feet below the surface of the earth. Unfortunately, the samples were too few to determine where the sharp increase took place nor what conductivity the soil might possess in the lower strata.

When either conductivity or dielectric constant changes from one homogeneous medium to another, as is the case at the Woodbridge Research Facility, a second medium for reflection is provided. Because these boundaries are close to each other, the energy which is transmitted through the primary boundary will undergo a second reflection at the secondary boundary. The wave which will ultimately be seen by an observer will be a combination of an incident wave, a primary reflected wave, and a series of multiply reflected waves. This problem is discussed briefly after the reflection from the primary boundary is discussed.

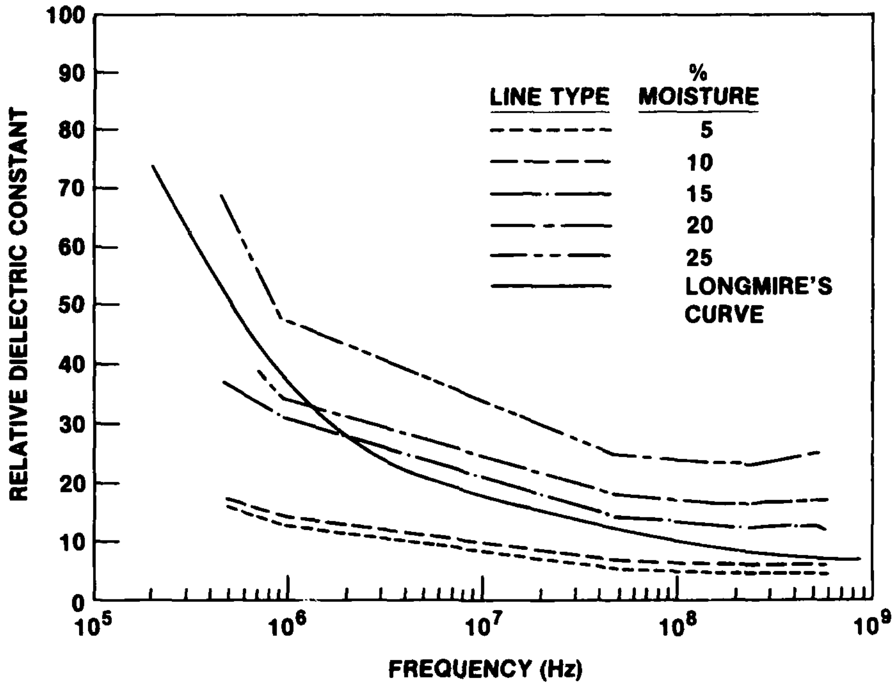

Figure 2. Relative dielectric constant versus frequency at sample points between 0.5 and 600 MHz. Longmire's curve for 10-percent moisture is also shown for comparison.

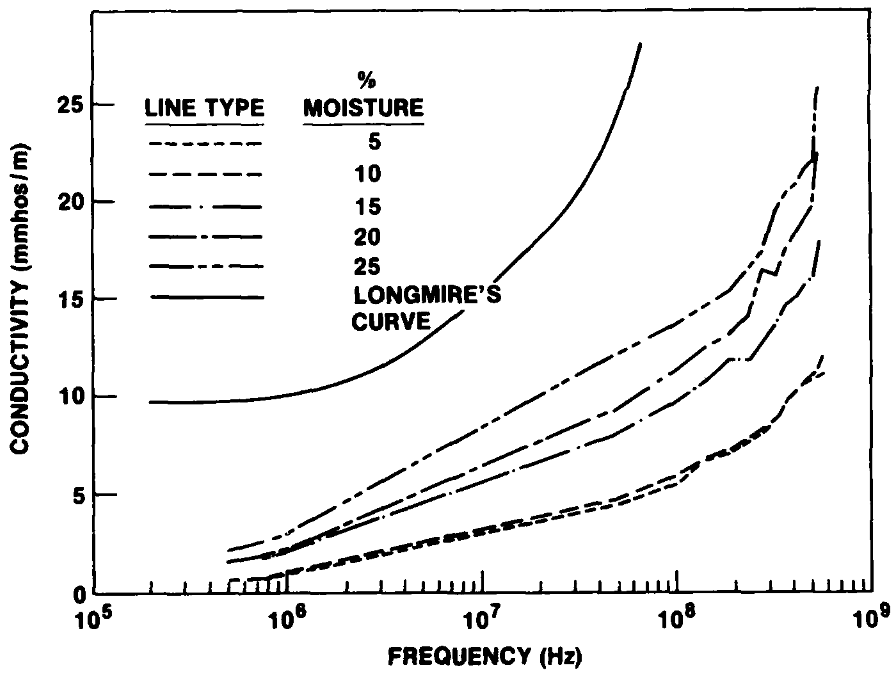

Figure 3. Conductivity versus frequency at sample points between 0.5 and 600 MHz. Longmire's curve for 10-percent moisture is also shown for comparison.

3. REFLECTION COEFFICIENTS FROM SOILS

3.1 Single Reflection

Soils, like most common materials, fall in the category of lossy dielectrics. Fresnel's equations (as discussed in many electromagnetics texts[3]) describe the reflection/transmission process of electric and magnetic components of an electromagnetic field across the boundaries of two distinct media. The following equations relate to figures 4 and 5.

For the E field normal to the plane of incidence,

$$E_1 = \frac{\mu_2 k_1 \left(\cos \theta_2 + \cos \theta_0\right)}{\mu_2 k_1 \cos \theta_2 + \mu_1 k_2 \cos \theta_1} E_0 \quad , \tag{7}$$

$$E_2 = \frac{\mu_2 k_1 \cos \theta_0 - \mu_1 k_2 \cos \theta_1}{\mu_2 k_1 \cos \theta_2 + \mu_1 k_2 \cos \theta_1} E_0 \quad . \tag{8}$$

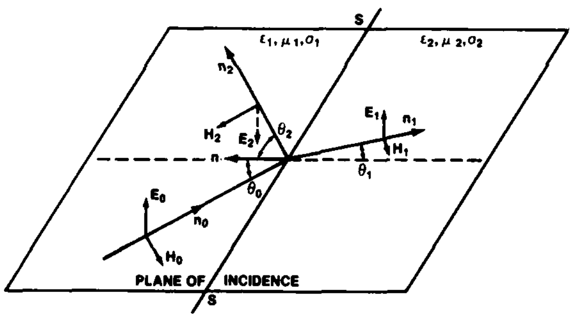

Figure 4. Polarization normal to plane of incidence.

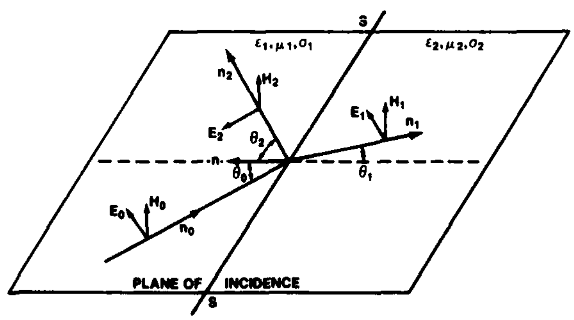

Figure 5. Polarization parallel to plane of incidence.

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[3] *J. A. Stratton, Electromagnetic Theory, McGraw-Hill Book Co. (1941).*

For the H field normal to the plane of incidence,

$$H_1 = \frac{\mu_1 k_2 \left(\cos \theta_2 + \cos \theta_0\right)}{\mu_1 k_2 \cos \theta_2 + \mu_2 k_1 \cos \theta_1} H_0 \quad , \tag{9}$$

$$H_2 = \frac{\mu_1 k_2 \cos \theta_0 - \mu_2 k_1 \cos \theta_1}{\mu_1 k_2 \cos \theta_0 + \mu_2 k_1 \cos \theta_1} H_0 \quad , \tag{10}$$

where θ is angle of incidence, and k_i is the complex propagation constant defined by

$$k_i^2 = j\omega\mu_i \left(\sigma_i - j\omega\varepsilon_i\right) \quad ,$$

where $\omega = 2\pi f$.

Through Snell's law

$$\sin \theta_0 = \sin \theta_2 \quad , \text{ and}$$

$$k_2 \sin \theta_0 = k_1 \sin \theta_1 \quad .$$

The reflection coefficients can be written

$$R_H = \frac{E_2}{E_0} = \frac{\mu_2 k_1 \cos \theta_0 - \mu_1 \sqrt{k_2^2 - k_1^2 \sin^2 \theta_0}}{\mu_2 k_1 \cos \theta_0 + \mu_1 \sqrt{k_2^2 - k_1^2 \sin^2 \theta_0}}$$

for E normal to the plane of incidence, and

$$R_V = \frac{H_2}{H_0} = \frac{\mu_1 k_2^2 \cos \theta_0 - \mu_2 k_1 \sqrt{k_2^2 - k_1^2 \sin \theta_0}}{\mu_1 k_2^2 \cos \theta_0 + \mu_2 k_1 \sqrt{k_2^2 - k_1^2 \sin \theta_0}}$$

for H normal to the plane of incidence.

By considering a typical air/earth interface, these formulas can be further simplified. Medium 2 (characterized by σ_2, μ_2, ε_2) is that of the earth, and medium 1 (characterized by σ_1, μ_1, ε_1) is that of air; since

$$\mu_1 \simeq \mu_2 \simeq \mu_0 \quad ,$$

$$\varepsilon_1 \simeq \varepsilon_0 \quad ,$$

$$\sigma_1 \simeq 0 \quad ,$$

the reflection coefficients can be simplified to

$$R_H = \frac{\cos\,\theta_0 - \sqrt{\left(\varepsilon_r - j\,\dfrac{\sigma_2}{\varepsilon_0\omega}\right) - \sin^2\,\theta_0}}{\cos\,\theta_0 + \sqrt{\left(\varepsilon_r - j\,\dfrac{\sigma_2}{\varepsilon_0\omega}\right) - \sin^2\,\theta_0}} \tag{11}$$

and

$$R_V = \frac{\left(\varepsilon_r - j\,\dfrac{\sigma_1}{\varepsilon_0\omega}\right)\cos\,\theta_0 - \sqrt{\left(\varepsilon_r - j\,\dfrac{\sigma_1}{\varepsilon_0\omega}\right) - \sin^2\,\theta_0}}{\left(\varepsilon_r - j\,\dfrac{\sigma_1}{\varepsilon_0\omega}\right)\cos\,\theta_0 + \sqrt{\left(\varepsilon_r - j\,\dfrac{\sigma_1}{\varepsilon_0\omega}\right) - \sin^2\,\theta_0}} \quad , \tag{12}$$

where $\varepsilon_r = \varepsilon_1/\varepsilon_0$ and subscripts H and V refer to horizontal and vertical components.

Figures 6, 7, 8, and 9 show the magnitudes and phases of reflection coefficients R_H and R_V using varying regional parameter equations. The angle of incidence is 60°.

The incident and reflected waves combine to form what is generally referred to as the total wave. These equations have been developed in other texts[4] and are restated here:

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[4]*M. A. Messier, The Effects of Ground Reflection on Observed EMP Waveforms, Defense Nuclear Agency, DNA 3370T (1974).*

$$E_H = E_0 \left[1 + R_H e^{-j(h/\lambda)}\right] \cos \phi \quad , \tag{13}$$

$$E_V = E_0 \left[1 + R_V e^{-j(h/\lambda)}\right] \sin \phi \cos \theta \quad , \tag{14}$$

$$E_R = E_0 \left[1 + R_V e^{-j(j/\lambda)}\right] \sin \phi \cos \theta \quad , \tag{15}$$

where

λ ≡ wavelength,
h ≡ distance between point of reflection and observer,
ϕ ≡ polarization of E vector, parallel to vector n,
E_R ≡ radial wave, and
E_0 ≡ incident wave.

These equations apply to the geometry of figure 10 and assume that the distance between the source of the pulse and either the observer or the earth is much greater than the distance between the earth and the observer.

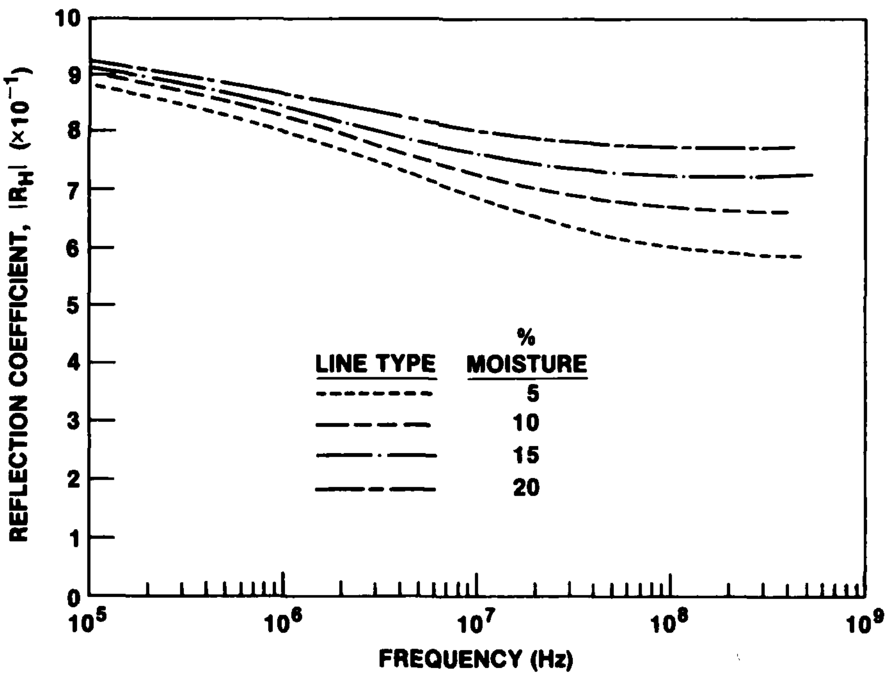

Figure 6. Magnitude of reflection coefficients (R_H) using varying-parameter model at 5-, 10-, 15-, and 20-percent moisture.

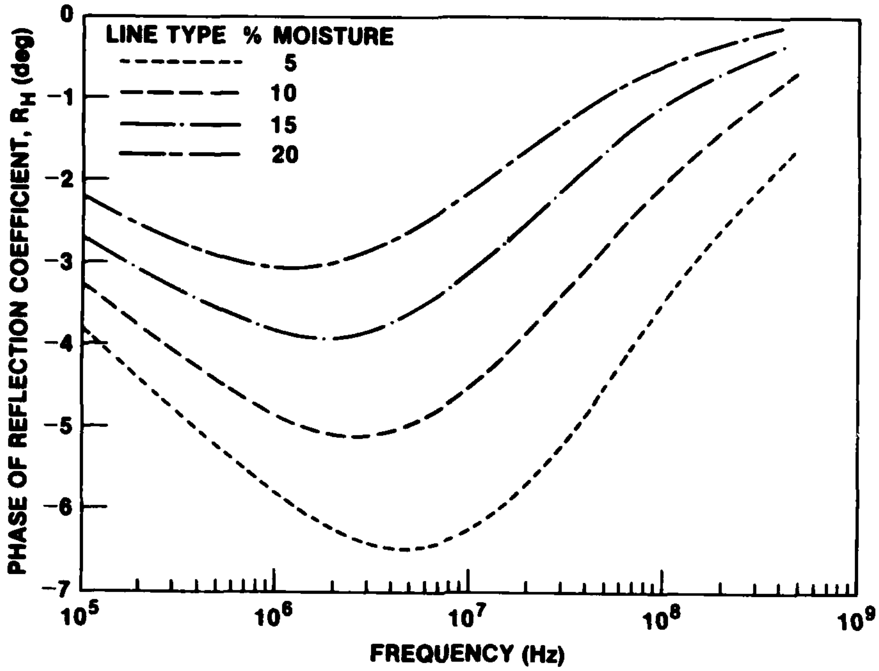

Figure 7. Phase of reflection coefficients (R_H) using varying-parameter model at 5-, 10-, 15-, and 20-percent moisture.

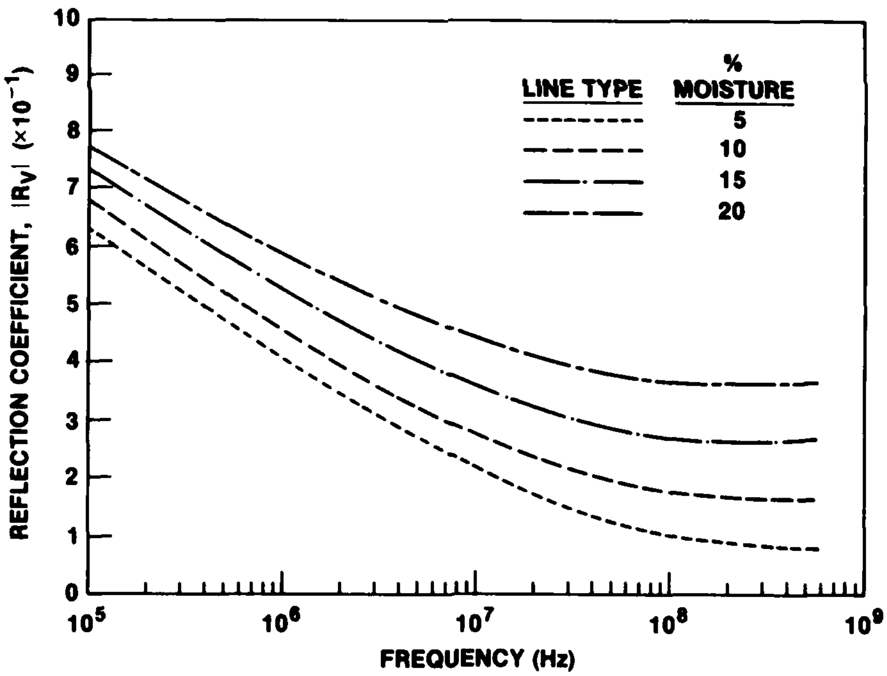

Figure 8. Magnitude of reflection coefficients (R_V) using varying-parameter model at 5-, 10-, 15-, and 20-percent moisture.

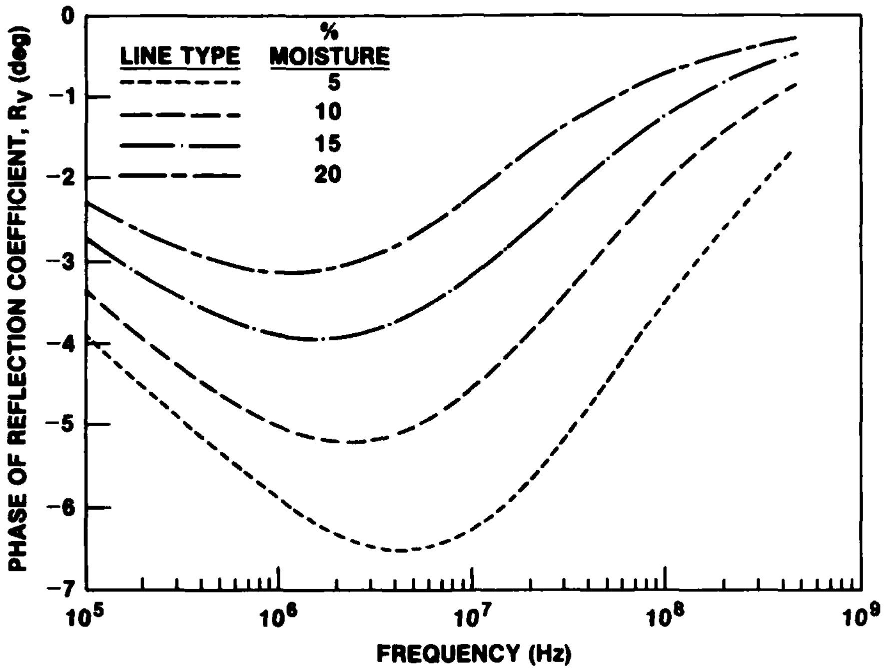

Figure 9. Phase of reflection coefficients (R_V) using varying-parameter model at 5-, 10-, 15-, and 20-percent moisture.

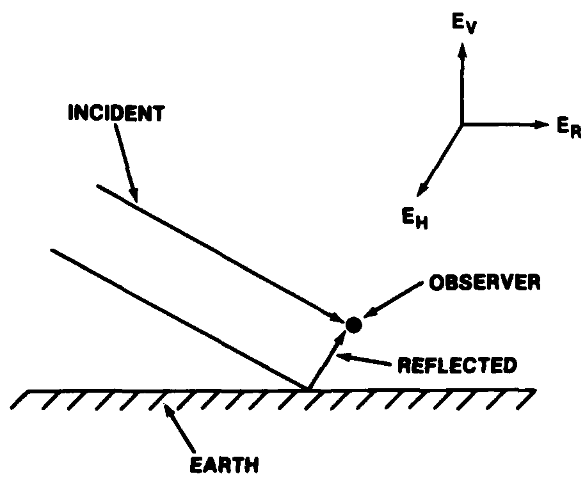

Figure 10. Singly reflected wave.

3.2 Multiple Reflection

If there is a marked increase in soil conductivity at some depth, as is the case for most of the eastern seaboard,[5] a transmitted pulse will undergo a primary reflection and a series of multiple reflections. Figure 11 depicts this process. The total wave seen by an observer just above the earth will be composed of an incident wave, a primary reflected wave, and a series of multiply reflected waves.[6]

The multiply reflected pulse is a geometric series:

$$E_r = E_0\left[1 + e^{j\Delta_1}\left(\rho + \tau\tau'\rho' e^{j\Delta_2} + \tau\tau'\rho'^2\rho'' e^{j2\Delta_2} + \tau\tau'\rho'^3\rho''^2 e^{j3\Delta_2} \ldots\right)\right] \tag{16}$$

(for zero polarization)

where

E_r = resultant E field,
ρ = reflection coefficient,
τ = transmission coefficient,
Δ_1 and Δ_2 account for phase delay and attenuation in medium 1 and medium 2, respectively, and
primes indicate the number of times the wave has been reflected.

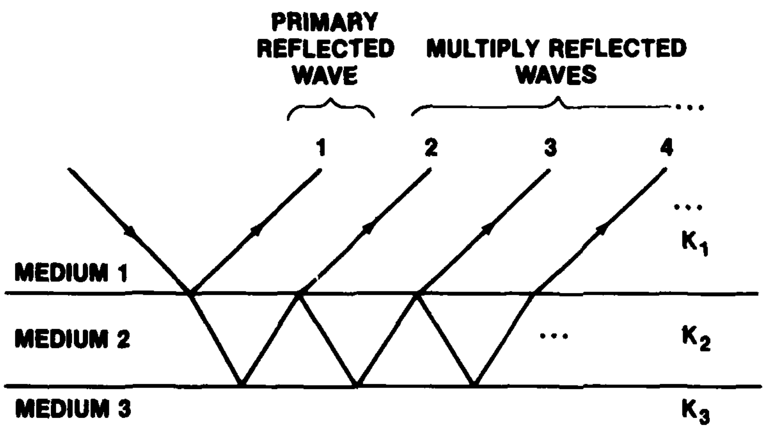

Figure 11. Multiply reflected wave.

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[5] E. D. Sunde, *Earth Conduction Effects in Transmission Systems*, D. Van Nostrand Co. Inc. (1968).
[6] M. V. Klein, *Optics*, T. Wiley and Sons Inc. (1970).

Equation (16) can be reduced to the closed-form equivalent:

$$E_r = E_0\left[\tau\tau'\rho' \, e^{j\Delta_1}\left(\frac{1}{1 + \rho\rho' \, e^{j\Delta_1}}\right)\right] . \tag{17}$$

Phase delay and attenuation can be found by

$$\Delta_1 = \frac{2h\omega}{\cos\theta_1}\left|\frac{\mu_2\varepsilon_2}{2}\sqrt{1 + \left(\frac{\sigma_2}{\omega\varepsilon_2}\right)^2} - 1\right|^{1/2} ,$$

$$\Delta_2 = \Delta_1 + \frac{2h\omega}{\cos\theta_1}\left|\frac{\mu_2\varepsilon_2}{2}\sqrt{1 + \left(\frac{\sigma_2}{\omega\varepsilon_2}\right)^2} + 1\right|^{1/2} ,$$

with

$$\rho_H = \frac{k_1 \cos\theta_0 - \sqrt{k_2^2 - k_1^2 \sin^2\theta_0}}{k_1 \cos\theta_0 + \sqrt{k_2^2 - k_1^2 \sin^2\theta_0}} , \tag{18}$$

$$\rho_H' = \frac{\sqrt{k_2^2 - k_1^2 \sin^2\theta} - \sqrt{k_3^2 - k_1^2 \sin^2\theta}}{\sqrt{k_2^2 - k_1^2 \sin^2\theta} + \sqrt{k_3^2 - k_1^2 \sin^2\theta}} , \tag{19}$$

$$\tau_H = \frac{2k_1 \cos\theta_0}{k_1 \cos\theta_0 + \sqrt{k_2^2 - k_1^2 \sin^2\theta_0}} , \tag{20}$$

$$\tau_H' = \frac{2\sqrt{k_2^2 - k_1^2 \sin^2\theta}}{\sqrt{k_2^2 - k_1^2 \sin^2\theta} + \sqrt{k_3^2 - k_1^2 \sin^2\theta}} , \tag{21}$$

for E-field normal to plane of incidence, and

$$\rho_V = \frac{k_2^2 \cos\theta_0 - k_1\sqrt{k_2^2 - k_1^2 \sin^2\theta_0}}{k_2^2 \cos\theta_0 + k_1\sqrt{k_2^2 - k_1^2 \sin^2\theta_0}} , \quad (22)$$

$$\rho_V' = \frac{k_3^2\sqrt{k_2^2 - k_1^2 \sin^2\theta_1} - k_2^2\sqrt{k_3^2 - k_1^2 \sin^2\theta_1}}{k_3^2\sqrt{k_2^2 - k_1^2 \sin^2\theta_1} + k_2^2\sqrt{k_3^2 - k_1^2 \sin^2\theta_1}} , \quad (23)$$

$$\tau_V = \frac{2k_2^2 \cos\theta_0}{k_2^2 \cos\theta_0 + k_1\sqrt{k_2^2 - k_1^2 \sin^2\theta_0}} , \quad (24)$$

$$\tau_V' = \frac{2k_2^2\sqrt{k_2^2 - k_1^2 \sin^2\theta_1}}{k_3^2\sqrt{k_2^2 - k_1^2 \sin^2\theta_1} + k_2^2\sqrt{k_3^2 - k_1^2 \sin^2\theta_1}} , \quad (25)$$

for E-field parallel to plane of incidence.

The reflection coefficients (R_H) for multiply reflected waves in a stratified medium are shown in figures 12, 13, and 14 (eq (18) through (21)). Figures 15, 16, and 17 show R_V for multiply reflected waves (eq (22) through (25). Here, the depth of medium 2 is 1/2, 1, and 2 m, respectively. Media 1 and 3 are considered infinite. The propagation constant k_1 is that of free space. Constant k_2 was generated from the variable regional parameter equation and k_3 was generated using the network model. The angle of incidence is 60°.

As can be expected, for the multiply reflected wave, the lower frequency components are more readily transmitted through the soil/soil boundary. At higher frequencies, a declining magnitude is due to increased attenuation in addition to increased soil conductivity.

Since the properties of the upper stratification below 10^5 Hz are not known, and the properties of the lower stratification are only conjectured to follow the universal network model, this analysis is not included in the final analysis of the reflected pulse; however, it is discussed here to show how a homogeneous model which uses either the universal network model or the variable regional parameter model may deviate from a possible real situation.

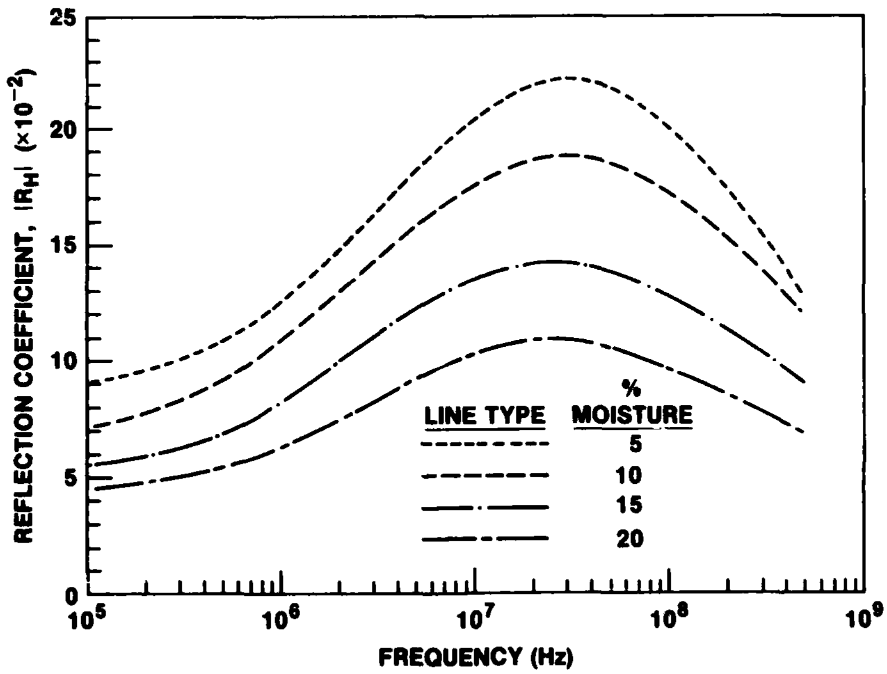

Figure 12. Magnitude of multiple reflection coefficient (R_H) for a two-layer earth. Varying-parameter model is used for upper layer (0.5 m thick), and network model is used for lower layer (infinite half plane).

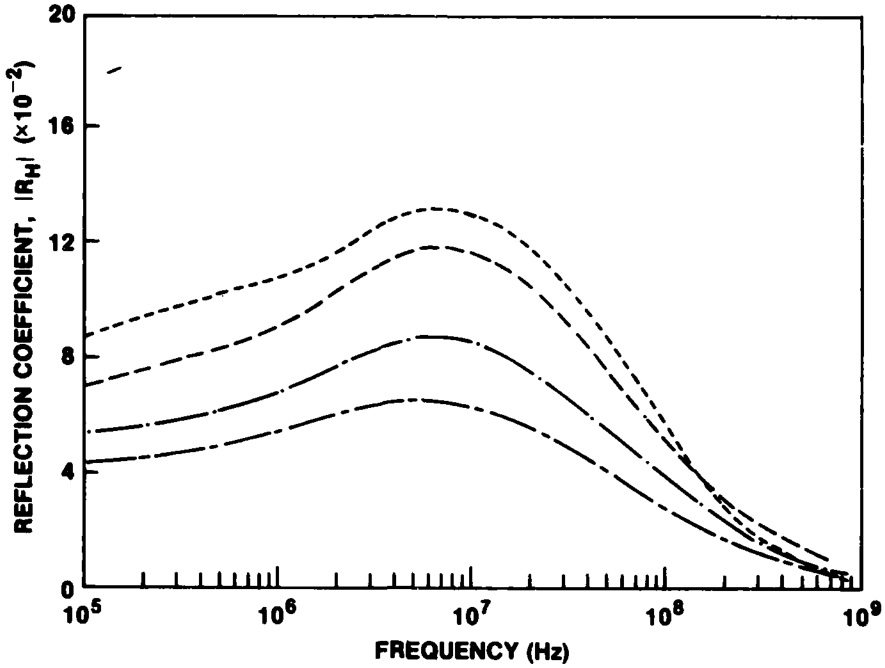

Figure 13. Magnitude of multiple reflection coefficient (R_H) for a two-layer earth. Varying-parameter model is used for upper layer (1 m thick), and network model is used for lower layer (infinite half plane).

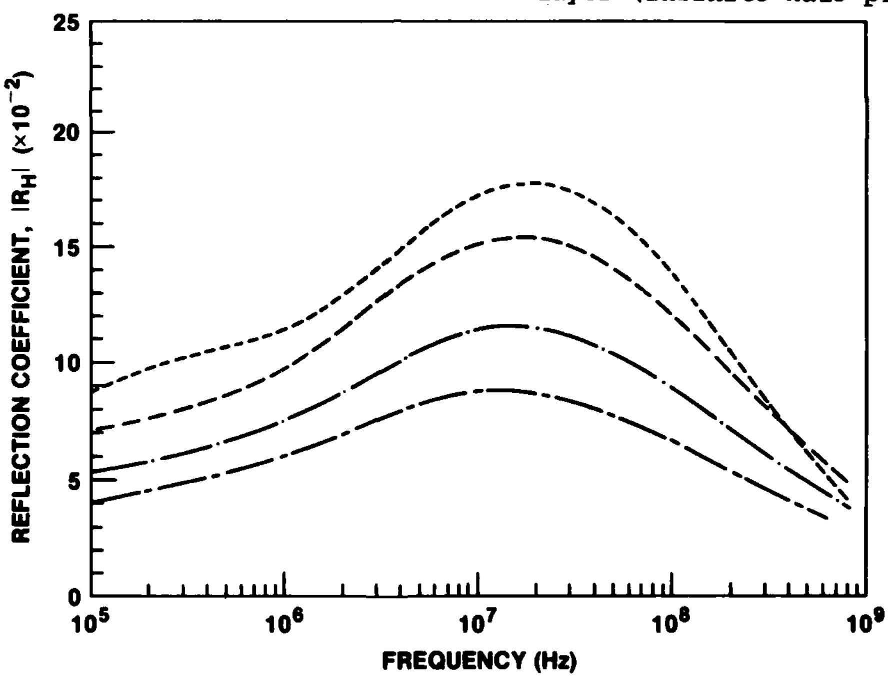

Figure 14. Magnitude of multiple reflection coefficient (R_H) for a two-layer earth. Varying-parameter model is used for upper layer (2 m thick), and network model is used for lower layer (infinite half plane).

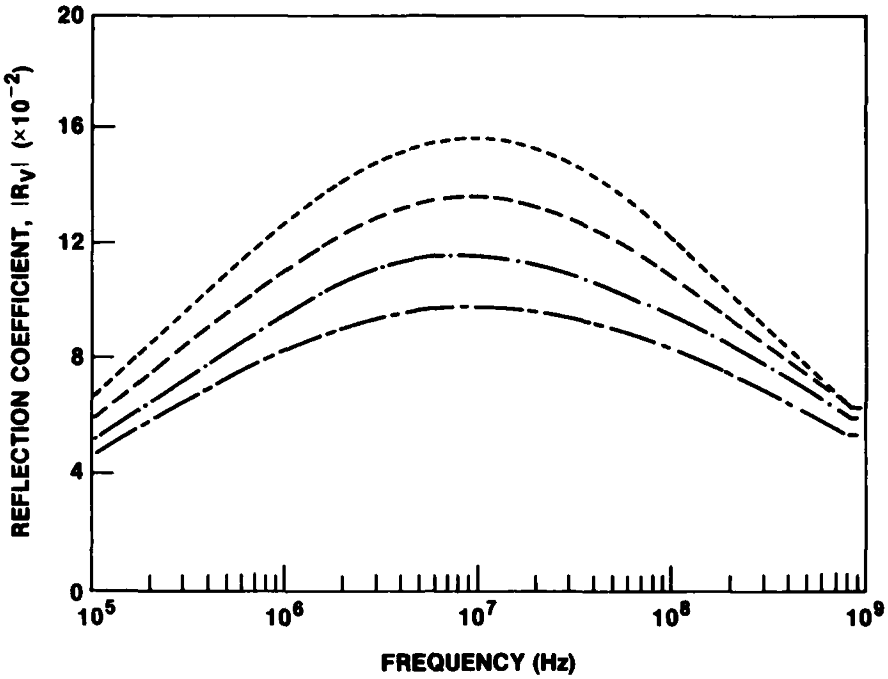

Figure 15. Magnitude of multiple reflection coefficient (R_V) for a two-layer earth. Varying-parameter model is used for upper layer (0.5 m thick), and network model is used for lower layer (infinite half plane).

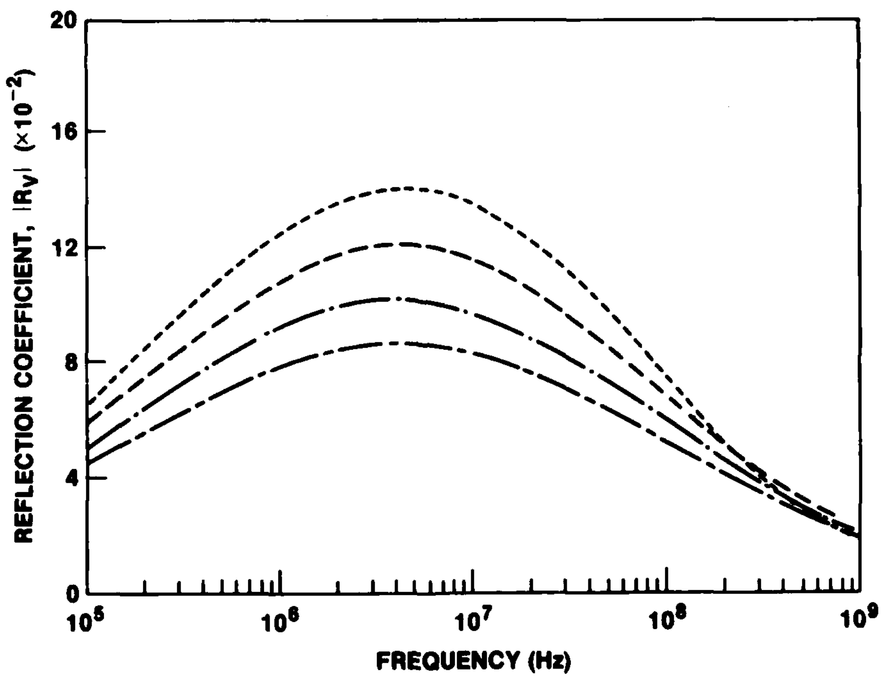

Figure 16. Magnitude of multiple reflection coefficient (R_V) for a two-layer earth. Varying-parameter model is used for upper layer (1 m thick), and network model is used for lower layer (infinite half plane).

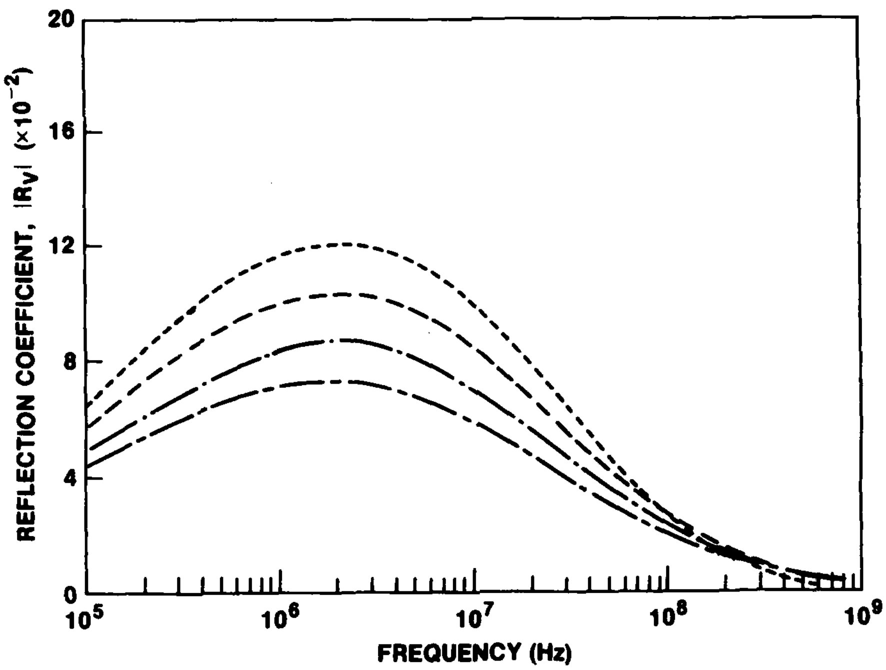

Figure 17. Magnitude of multiple reflection coefficient (R_V) for a two-layer earth. Varying-parameter model is used for upper layer (2 m thick), and network model is used for lower layer (infinite half plane).

4. ERROR ANALYSIS

A convenient way to represent the total energy on a per ohm basis is by integrating the magnitude of the spectral density over the range of frequencies of interest:

$$E = \frac{1}{2\pi} \int_{-\infty}^{\infty} |E(\omega)|^2 \, d\omega \quad . \tag{26}$$

The energy difference between two real spectra is

$$\frac{1}{\pi} \int_{0}^{\infty} |E(\omega)|^2 - |\bar{E}(\omega)|^2 \, d\omega \quad . \tag{27}$$

Here, $E(\omega)$ represents the spectrum of the total E field of the signal used as the basis for analysis, and $\bar{E}(\omega)$ is the approximating signal. The percentage of error (P_e) is

$$P_e = \frac{\int_0^\infty \{|E(\omega)|^2 - |\bar{E}(\omega)|^2\}\, d\omega}{\int_0^\infty |E(\omega)|^2\, d\omega} \times 100\% \quad . \tag{28}$$

Since it is not possible to numerically integrate over the entire spectrum, the analysis will include the extrapolated spectrum of 10^5 to 10^9 Hz in which the variable parameter model is valid. Also, to eliminate the confusion or cancellation due to phase shift caused by the delay of the reflected wave, the observer is placed an incremental distance above the earth's surface. Here also, the analysis is done for zero polarization (i.e., R_V is not used). Table 2 lists the percentages of error between the total energies of waves above soil modeled by the variable-parameter model and soil modeled by the network model with the variable-parameter model as the standard.

The values show that the spectra $E(\omega)$ and $\bar{E}(\omega)$ are displaced from each other and will probably give values for P_e which will be no less than 50 percent.

Another model which is often used for calculating propagation constants and reflection coefficients is the constant-parameter model. This model, as the name implies, assumes that the conductivity and dielectric constant are constant over the entire spectrum of frequencies and range of possible moisture contents. Typical values for these parameters are σ = 7 mmho/m and ϵ_r = 15 for the Woodbridge Research Facility. The values for the percentage of error are listed in table 3.

These values indicate that by judicious selection of σ and ϵ_r the percentage of error can be reduced. However, some error is inevitable because the spectrum predicted by the constant-parameter model will have a sharper roll-off, as demonstrated in the comparison of the three models given in figure 18.

TABLE 2. PERCENTAGE OF ERROR FOR VARIABLE-PARAMETER MODEL (STANDARD) AND NETWORK MODEL FOR VARIOUS MOISTURE CONTENTS

Moisture content (%)	Percentage of error (%)
5	59.0
10	-75.2
15	-80.4
20	-82.7

TABLE 3. PERCENTAGE OF ERROR FOR VARIABLE-PARAMETER MODEL (STANDARD) AND CONSTANT-PARAMETER MODEL FOR VARIOUS MOISTURE CONTENTS

Moisture content (%)	Percentage of error (%)
5	68.9
10	63.0
15	54.4
20	43.8

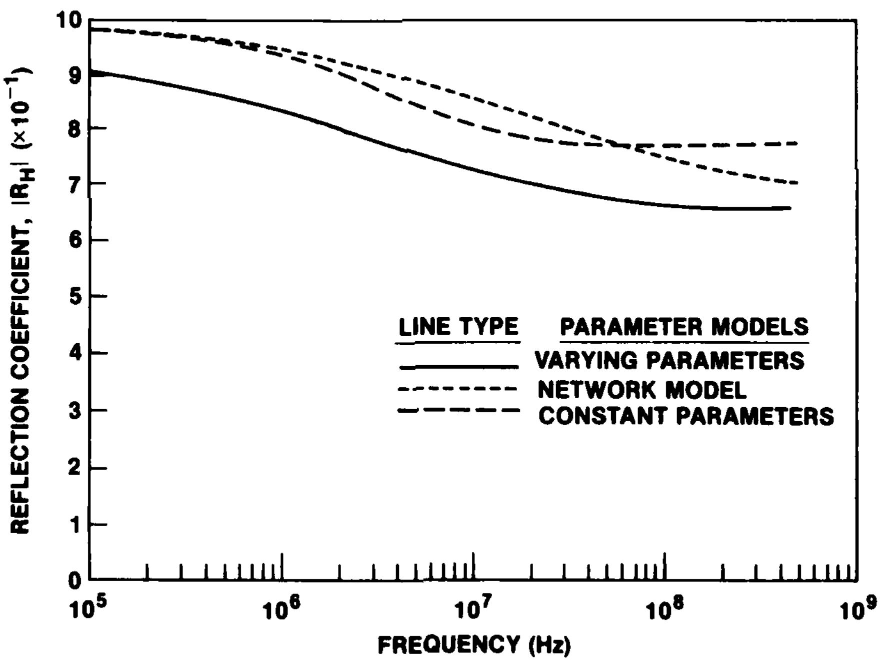

Figure 18. Comparison between reflection coefficient as predicted by varying regional parameter model, network model (both at 10-percent moisture), and constant-parameter model (conductivity = 7 mmho/m, dielectric constant = 15).

5. CONCLUSION

The percentage of error for the energy difference between two signals was minimized by using the constant-parameter model. This, however, does not mean that the constant-parameter model is the best possible method. The spectra of the reflected wave had a sharper roll-off than either the variable-parameter model or the network model. This means that there will be some minimum error which cannot be eliminated.

If there were data between 10^2 and 10^6 Hz, the network model could be altered to more closely approximate the true nature of the soil. A convenient method for obtaining the soil parameter at any frequency and moisture content would then exist. It could conceivably minimize the percentage error below 10 percent.

However, the problem generated by the multiple reflection from a stratified medium would still remain. The only solution for this would be to follow the stated equations for multiple reflections after the lower stratification has been characterized by extensive field measurements.

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